

Analysis of Field Procedures and Hydrocarbon Concentration Data
From the Soil Vapor Monitoring Program
Red Hill Bulk Fuel Storage Facility

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Executive Summary

The present report is an evaluation of the Soil Vapor Monitoring Program currently being maintained beneath the Red Hill Bulk Fuel Storage Facility and an interpretive analysis of the soil vapor data that have been accumulated over the duration of that program with special emphasis on data collected immediately before, and for the years after, the 2013-2014 fuel release from Tank 5. The goals of this effort are to: identify possible sources of data uncertainty in the field sampling and analysis protocols; recommend testing and modifications to the field procedures that will minimize those errors to the greatest practicable extent; analyze and interpret the data recovered to the present date in an effort to understand how a new release is expressed in the measured soil vapor concentration data below the leaking tanks; provide an interpretation of broad scale transport as well as environmental processes that may affect vapor values and vapor detections; and, finally, to provide guidance in the development of appropriate response protocols for future detection of elevated soil vapor values.

The analysis of the field protocols has identified several potential sources of error arising from field procedures, equipment storage, and instrument calibration and recommends testing and alterations in those procedures that will improve quality assurance of the data.

Interpretive analysis of the recovered data at the time of the 2013-2014 fuel release shows that vapor values below Tank 5 were responding to the release within a few days of the initiation of tank refilling operations; vapor values in the tanks adjacent to Tank 5 also show substantial increases very soon after the increases at Tank 5; and during subsequent weeks and months, the vapor values beneath tanks at least as far away as Tanks 10 – 12 were impacted by the Tank 5 release. The data strongly suggest that the released LNAPL passed through the unsaturated zone, downslope below Tank 3 and may have reached the water table. The long-range transport of vapor is inferred to suggest that there is thermally-induced gas phase advection of volatile hydrocarbons through the vadose zone. The vapor data also show a complex response to environmental effects, specifically high rainfall accumulations, that suggests groundwater mobilization of fuel and, possibly, mobilization of residual fuel contained within the concrete tank encasements out into the vadose zone, producing short term elevations in vapor concentrations immediately below tanks where leakage has occurred while suppressing long-range vapor transport to the more distal, upslope tanks.

These findings recommend the development of a response protocol that employs a dynamic threshold for conditional responses to elevated vapor detections above prior average values within vapor probes from each tank. At minimum, that response would include immediate confirmation or refutation of a new release followed by appropriate actions that would minimize the volume of lost fuel and reduce the scale and cost of the response and mitigation of that release.

Introduction

At the request of DOH staff, I have reviewed the Soil Vapor Monitoring Program at the Red Hill Bulk Fuel Storage Facility (RHBFSF). The analysis has evaluated the field protocols, to the extent that the DOH staff and I have been able to gather data on the field procedures, as well as the data derived from the monitoring program. The ultimate goals of this effort are to:

- 1) determine what insights can potentially be gained regarding fuel release and transport from the currently available data;
- 2) identify where quality assurance practices can be incorporated into the field sampling and analysis procedures to reduce uncertainties in measured vapor concentrations;
- 3) ensure that future soil vapor monitoring data can be relied on as the basis for a decision-making and response tool that will enable the facility operators to detect and appropriately respond to new releases in as short a time as practicably possible; and thereby
- 4) minimize the loss of fuel and the cost and impacts associated with future releases.

In the analysis of the field protocols, I have relied on documents provided to me regarding requirements for the field procedures to be applied as well observations of field procedures by DOH staff and reports of discussions between DOH staff and field technicians and facility operations staff. The information I have been provided may be incomplete and, hence, recommendations made for improvements to the field procedures are provisional and subject to further discussions with facility staff and field technicians.

In my review of the field data, I have reviewed the reported average vapor values provided to DOH since 2008. In my review, I have:

- analyzed the changes in reported vapor concentration data among the full suite of vapor probes for their responses to known fuel releases;
- compiled environmental data (e.g. monthly rainfall accumulations) and evaluated the relationship between variations in vapor concentrations and environmental variables as well as other possible influences;
- assessed the value of the measurements in the context of early warning of new releases;
- made recommendations as to alternative monitoring protocols that may offer advantages over the current approach.

Background

The stated purpose of the soil vapor monitoring program is to detect evidence of leakage of stored fuels from the RHBFSF as early in the process as possible. The underlying theory is that, in the absence of leaked fuel, the hydrocarbon content of soil gases should be at negligible concentrations but, after a release occurs, fuel leaked through the steel tank walls will migrate through cracks and pores in the reinforced concrete encasement and migrate into the vadose

(unsaturated) zone where it will descend through the porous basalts toward the underlying groundwater. As the fuel enters the vadose zone, the more volatile constituents will vaporize and disperse through the open pore space of the basalt lava flows that make up the interior of Red Hill Ridge. Larger amounts of released fuel would be expected to lead to higher initial concentrations of hydrocarbons, whereas smaller volumes would yield lower and less persistent concentrations of volatile hydrocarbons. Over time, the composition of the vapor phase would change as the more volatile constituents become depleted from the liquid phase and biodegradation removes the more easily consumed (light, short-chained) constituents. These processes, as well as dispersal, would be expected to reduce hydrocarbon concentrations but, as will be discussed later, other processes could reverse that trend for short periods of time.

In order to detect changes in hydrocarbon vapor concentrations, suites of three vadose-zone vapor sampling probes were installed beneath the active tanks used at the RHBFSF during the 2007 – 2008 timeframe and have been sampled on approximately a monthly basis since that date. The probes are configured as shown in Figure 1: three 0.1250" diameter soft copper (or stainless steel) tubes are nested inside a 3.5" diameter borehole, inclined downward at 15° from horizontal, with the tubes running down the inclined bore for distances of 25', 60', and 95' respectively. The three insertion distances are intended to monitor vapor from infiltrating fuel at the inner edge (closest to the tunnel wall) of the tank, at the middle of the tank, and at the outer edge of the tank (hereinafter designated as shallow, middle, and deep probes); the bottom 10' of each tube is perforated with 3/16" holes, at 2' intervals, for vapor sample intake; each probe intake is isolated from its neighboring probe by a 7' plug of bentonite; the depth of open interval below the bottom of the steel tank base for each probe is estimated at 26.5' (for the shallow probe), 35.5' (for the middle probe), and 44.5' (for the deep probe).

It is my understanding that probe sets were installed beneath all 20 tanks; however, the data set that I have been provided omits data from any probes beneath Tank 1 and Tank 19; likewise, data is missing for the entire monitoring interval for the deep probe beneath Tank 6; the shallow probe beneath Tank 11; and other individual probes have extended periods of no values reported. Some of the latter gaps in data, reportedly, occurred during periods when the tanks were out of service for maintenance; and some for periods during which the probe lines may have been inoperable. In general, for those probes for which data are reported, the sampling interval appears to be approximately monthly but, during early sampling (prior to 2013) variations of as much as two to three weeks from that monthly interval are present; since 2013, the sampling is more regular except for the period immediately after the December 2013 fuel release when more frequent sampling was done for some of the probe sets close to Tank 5.

Sampling Procedure

The samples are withdrawn from each probe and analyzed using a hand-held organic vapor photo-ionization detector (PID) instrument capable of detecting organic vapors down to 1 part per billion (ppb) (see attached product literature). It should be noted that this instrument is only able to determine the presence and an approximate concentration of organic vapors (approximate because different organic compounds are more or less susceptible to ionization and, therefore, signal generation); it is not able to provide information on the composition of

the organic vapor constituents. The PID is, reportedly, zeroed and calibrated with reagent gases containing a zero concentration and a known concentration of organic vapor at the start of each sampling day (this procedure has now been altered by the current contractor to multiple times during the sampling and analysis exercise). Vendor literature claims a precision of 1 ppb when calibrated for a range from 1 to 9,999 ppb; 10 ppb for a range of 10,000 to 99,000 ppb; and 100 ppb for a range of 100,000 to 999,000 ppb. The instrument is able to pump ~500 cc/min of sample through the detector assembly.

Anecdotally, I have been told (by HM) that the probe lines are cleared of stagnant vapor by pumping and discarding the pump exhaust. Samples for analysis are then withdrawn from the probe lines through flexible tubing that is attached to a Tedlar® bag and the bag is inflated by vacuum suction. The vapor samples are then pumped from the Tedlar® bag through the PID sensor by the instrument; three readings are taken and the values averaged to yield the reported value. DOH staff (HM) who has witnessed the sampling and analysis procedure have indicated that purging of the individual lines is done for a few minutes, but no specific volume of soil gas is withdrawn during that process; further, withdrawal of samples for analysis is also done for a set time period, but without regard to the volume of soil gas withdrawn. It is also my understanding that the flexible tubing and Tedlar® bags used for the sampling from each probe are stored on-site within the chamber housing the probe-end valves.

Evaluation of Sampling and Analysis Procedures

Potential Sources of Error in Current Sampling/Analysis Procedure

If the information I have been provided on the sampling and analysis procedure are accurate, I believe that there are a number of steps and practices in the procedure being used that have potential to render the data less precise and less reliable than they could be.

1. According to the DOH witness (HM), some probes yield gas freely, but some only with difficulty. The apparent randomness of the gas volumes removed during purging of the tubing and collected for analysis from each probe could result in both highly variable, and erroneous, sample results. It should be recognized that different probes will respond to pumping differently: some probes may be mounted in highly permeable rock formations and others may be mounted in zones having much lower permeability; some probe lines may be partially blocked whereas others may be free of any obstruction. (This inference is substantiated by the observations of DOH staff that similar pumping times yield very different fill volumes in the Tedlar® bags.) This will have several effects on both the pumped volumes as well as the vapor concentrations observed. In the less permeable formations, much lower volumes of gas will be withdrawn during a given pumping interval and, in the event of a significant rainfall event, the permeability may become even more limited until the rainfall recharge drains from the formation. Under low permeability conditions, if the attachment of the flexible tubing to the valve at the discharge end of the probe is not entirely secure, then there is also the possibility that ambient air is being drawn through the pump rather than soil vapors from the probe. Hence, as a result of the low permeability, the pumping interval may not actually clear the

tubing of the stagnant ground gas and a completely unreliable result will be obtained. (A secondary effect of the low permeability is that, in the event of a future release, the probes mounted in less permeable formations may respond much more slowly than those in more permeable formations. Hence, a set of probes in more permeable formations may respond to a release sooner than those in less permeable rocks even though the latter are closer to the point of release.)

Recommendation: It is essential that the probe lines be checked to ensure that they are clear of obstructions and that samples are being drawn from the formation around the probe end. These probes have been in place for more than a decade; they are located in what is supposed to be a normally unsaturated zone. But there is evidence that some of the probes have become clogged or obstructed by debris; which suggests that the cavities in which the probes have been mounted have been periodically flooded and possibly fouled by debris or drilling materials and, hence, are not drawing a representative sample of vapor from the formation. If it cannot be verified that the probe lines are clear, then those lines should be replaced.

Where serviceable lines are confirmed, a secure connection should be used to draw a measured volume of soil vapor from the installed vapor tubing before collection of a sample of gas for analysis. A secure connection can be achieved using stainless or Teflon Swagelok fittings. A test for tightness would be to partially evacuate the sample line with the terminal valve closed and a pressure transducer attached; if, vacuum is held in the line, then a secure connection has been made. Similarly, an appropriate, fixed standard volume of soil vapor should be drawn from each probe every time the sampling program is executed to ensure consistency among the probes and consistency between the monthly sampling exercises. At the very minimum, the tubing for each probe should be purged of stagnant gas by pulling a known, measured volume of soil gas (equal to 2 to 3 times the tubing volume - nominally 18.29 cc/m of 0.25 in. diameter tubing and ~4 cc/m of 0.125 in. diameter tubing - from each probe line and only then collecting a measured volume of sample for analysis.

I would also recommend that a validation exercise be conducted in which soil gas is drawn from each probe at a fixed, constant rate, while the gases from the pump discharge are tested repeatedly to ascertain whether, and when, a consistent analytical result is achieved for that probe. This will ensure that interaction between the vapor phase in the formation and the tubing walls during transport to the surface will be minimized.

It was recommended by a DOH consultant (GDB) that pressures also be monitored and recorded during the pumping exercise to ensure that no anomalies are observed there as well.

2. There appears to be no, or inconsistent, instrument validation from one set of probes to the next. Under the current protocols of reuse of tubing and sample bags (to be discussed further below) there should be a "span gas" and a "zero gas" sample run – using identical tubing and sample bag as that used for the sample - prior to sampling from each set of probes. Only if the span and zero gases yield appropriate results, should sampling proceed. Further, if there is a high reading for any of the individual probes for a specific tank, then there should be a

zero/baseline test done before the sample from the next probe is collected and analyzed. (This is to ensure that there is no “memory effect” occurring in the analysis system.)

3. The onsite storage method for the sample bags and flexible tubing has high potential for contamination of the stored equipment with hydrocarbon vapors - this could significantly impact the levels of hydrocarbon being detected. An incident reported by DOH staff (HM): there was a significant drop in the values reported for Tank 18, from ~7000 ppb to about 300 - 500 ppb for both active probes from the May to June (2019) sampling round that continued for subsequent samples. When he inquired about that change, he was told that the flexible tubing had been changed immediately prior to the start of the June sample collections. This gives strong credence to probable contamination of all the equipment stored on-site between sampling campaigns.

I would further note that, when examining the full suite of data for the tanks, there is a nearly universal pattern of significant changes in the reported values when there is a transition from one contractor to another. In the attached table, I show, in the far right column, the name of the contractor who was providing the analytical results; the results for each contractor’s first suite of samples has been highlighted in bold. The “new” results from that sampling exercise show deviations of as much as 400% from the prior sampling averages. In my opinion, if proper field procedures are being used such variances should not be occurring: although there is no way for me to know how the procedures may have varied from one contractor to the next, I can reasonably assume that the conditions at the intake point for the individual probes are unlikely to have changed solely because a new contractor is collecting the samples and, therefore, these deviations are largely the result of variances in the equipment used or the sample collection procedure.

Recommendation: At a minimum, each sample should be taken with tubing and a bag that are demonstrably free of contaminants. The most reliable and secure practice would be to use new tubing and new bags with each sampling exercise; the next most reliable practice would be to store all sampling and analysis equipment in a hydrocarbon vapor free atmosphere; re-use of the bags and tubing should only be allowed if it can be demonstrated that they are not retaining contaminants from prior sampling exercises. If there is an over-riding reason that they have to be stored on site, then both the tubing and bag should be checked for background readings using a zero gas (fill the bag through the flex tubing with zero gas, and take a baseline reading prior to sample collection). If it cannot be demonstrated that this sampling procedure can be accomplished without impacting the results produced, then an alternative sampling protocol should be implemented that eliminates the tubing and bag procedure entirely. Given the variations noted above (associated with different contractors) it is recommended that the new procedure be thoroughly tested to ensure that it is imposing minimal artifacts on the readings produced and that each step in the process be detailed according to well-defined conditions (volumes, rates, pressures, etc.) so that the procedure can be replicated in detail by new field technicians or new contractors.

4. The samples are collected on approximately a monthly interval. There has not, to my knowledge, been an effort to determine how the vapor concentrations may vary with time

during the day, or from day to day. Research conducted on soil gas transport has shown that subsurface soil gas is impacted by a number of surface phenomena; research in Hawaii has shown that this is especially true in Hawaii's porous rocks. Chief among the possible effects are those associated with changing barometric pressure as well as the effects of wind speed across the Red Hill Ridge due to the Bernoulli effect. Diurnal changes in barometric pressure typically cause air to migrate into the exposed soil during rising barometric pressures and allows soil gas to expand out of the soil column during falling barometric pressure. This effect is likely to impact only the relatively near-surface soil vapor concentrations. The longer term pressure variances caused by wind speed acting on Red Hill ridge are more likely to enhance or decrease air exchange deeper within the ridge. However, a more significant effect may be associated with the impacts of changing pressures within the lower adit: it is my understanding that the air pressure is maintained at a value slightly below the outside barometric pressure and could, depending on the quality of the seal within the adit walls, significantly contribute to air/vapor transport in the vicinity of the probe intakes. Changes in the relative vacuum within the adit due to operational changes could be expected to induce some variability in the soil vapor concentrations detected. (Another significant pathway for soil gas extraction from the subsurface is through the monitoring wells drawing soil vapor through the well screen above the water table, but this is unlikely to significantly impact vapor concentrations at the probe inlets.)

As discussed later in this report, there is strong evidence that thermal advection of the ground gas is occurring as a result of biodegradation of hydrocarbons retained in the vadose zone from prior releases. It is likely that advective transport will, in turn, be impacted by rainfall events: post rainfall decreases in formation temperatures may be reflected in reduced advective transport; saturation of less permeable formation with groundwater may alter vapor phase transport paths; extended drought periods may enhance transport as a result of decreased saturation and increased temperatures.

Recommendation: Ideally, withdrawal of soil gas with the pump discharge being sampled by the ppb RAE 3000 instrument until a stable vapor reading is achieved may be a more reliable sampling and analysis method but would need to be carefully tested against current methods to ensure that reproducible data were being generated.

As recently discussed (11/25/2020), continuous monitoring (or permanent installation of probes capable of higher frequency measurements) of vapor levels would provide much greater insight into how these effects are expressed in the vapor data. However, in order to recover the most value from the enhanced monitoring, it will need to be implemented carefully and should be undertaken in stages: continuous monitoring at the full suite of probes beneath an individual tank for a limited duration (1 – 2 weeks), followed by similar monitoring at several other tanks for limited durations would answer many outstanding questions that remain about the impacts of operational and environmental changes.

5. Recently, with a change in the contractors providing the sampling and analysis services to the Navy, I have been informed that the contractor has modified the procedure to include efforts to clear the lines of obstructions by injecting compressed air into the sampling ports.

Simultaneously, the data reported have shown substantially lower values and some readings of zero concentrations of hydrocarbon vapor. Given the unusual number of zero and extremely low readings, in the absence of other information to the contrary, it appears that the practice of clearing the vapor probe lines is having a substantial impact on the readings reported. It was reported (HM) that about 5 hours was allowed to elapse between the time of clearing the lines and the sampling and analysis process. If a substantial volume of air was injected through the lines, into the vapor space around the probe inlets, this may not be sufficient time for equilibrium to be re-established between the formation volatiles and the injected air volume.

Recommendation: If the probe lines are cleared using compressed air, I would recommend that a volume of at least several times that of the injected air be withdrawn before sampling OR a period of several days be allowed to elapse between clearing the lines and subsequent sampling. If pumping is done, then withdrawal of air from the probe should be continued until a constant vapor reading is achieved; even then, the resulting analysis may not be directly comparable to prior sampling and analysis exercises where no air was injected into the probe lines.

Summary Recommendation on Procedure for Sampling and Analysis

Soil vapor sampling has the potential to serve as a very useful monitoring method to determine, at an early stage, when fuel has escaped the confines of the steel tank and its concrete encasement. In order for this process to best serve this purpose, care needs to be exercised to ensure that the analysis results are an accurate representation of the vapor concentrations in the formation below the tanks. Significant effort invested in the design of the current sampling procedure, to ensure that the results are accurate (and reproducible) for a given sampling episode, will allow the Navy's facility operators to more reliably assess the condition of their tanks and to recognize, at an earlier stage of a release, that fuel is entering the vadose zone below the tanks. With that information they will be able to respond more quickly and more effectively to reduce the volume of the release and limit the impact of the release on the environment.

If continuous/more frequent monitoring is implemented at one or more probes, the data produced have the potential to allow the Navy to incorporate an understanding of the impacts of environmental (and operational) variables into their analysis of the data to better recognize variances associated with fuel releases and to respond and manage those releases with as little impact on the environment as possible.

Evaluation and Interpretation of Reported Analytical Results

Interpretation and Analysis of prior Vapor Probe Data

In very general terms, the vapor concentration data recorded over the course of the monitoring program spans a significant range: the lowest concentrations recorded are in the single digits of parts per billion (and possibly as low as the detection limit of the instrument, if the zero readings are accepted at face value); the highest values recorded are as high as 450,000 ppb. This upper level value is likely to be, at best, a rough approximation of the levels due to instrument saturation. During the early years of monitoring, a number of elevated values were reported for the higher-number Tanks (10 and above) and fewer elevated vapor values found in the lower numbered tanks. Although possibly of historical interest, the elevated measurements in the upper storage facility are outside the scope of the current report and won't be dealt with in detail here.

Visualization of the Data: The focus of the current report will be on the release from Tank 5 and the data variations that may be associated with that event. However, a brief digression is needed in order to provide a context for understanding the data presentations that will be offered below. The data produced by the vapor monitoring program presents some challenges for analysis and visualization due to both the large size of the data set as well as the broad aerial extent of the sampling locations. Typically, time series data are presented as plots of measurement/amplitude values on the "Y" axis and time on the "X" axis (Figure 2). In Figure 2 are plotted the vapor concentration values (on a linear vertical axis) for the three vapor probes below both Tank 3 and Tank 5. Clearly, the very high values for Tank 5 after the December, 2013 release are clearly visible, but don't allow us to examine any details in the concentration values for Tank 3 beyond seeing that the deep probe below Tank 3 spikes somewhat after elevated values were seen below Tank 5. Plotting these same values on a logarithmic axis allows us to better visualize the changes in vapor concentrations below Tank 3, but heavily mutes concentration variations of less than a factor of ten. It's also clear that plotting vapor probe data for more than two or three tanks will only yield a confusing cloud of lines and, hence, tracking the effects of the release on more distal subsurface vapor concentrations is, at best, difficult.

The concentration data for the entire tank installation can be plotted on what is called a "waterfall" plot (Figure 4, Hugh Meyers, personal communication). This plot allows visualization of the entire data set simultaneously, as a three-dimensional (3D) bar graph, and shows very quickly where very high vapor concentrations are occurring. The 2013 release at Tank 5 indicates the onset of extreme vapor concentrations and their later progressive decline; later high values, of short duration, are also evident at Tank 7, as well as smaller, but still elevated, values at Tanks 17 and 18. However, all bars are plotted on a single vertical axis scale and the very high values at any single site mutes the smaller variations in vapor concentration that occur in the surrounding vapor probes after the December 2013 release. Removing the values for Tank 5 vapor probes, Figure 5, does allow somewhat better visualization of the vapor increases in the adjoining tanks' probes, especially the extremely high values in the Tank 3 probe which occur beginning in late January, 2014, and extending into March, 2014. It should also be recognized that the time axis on these plots is not linear – the bar graphs for each probe are plotted in sequence whether samples were collected at daily intervals or monthly intervals

and, hence, the apparently large data gaps are generated by the frequent sampling at and around Tank 5 while maintaining a monthly sampling interval for the more distal tanks.

A third approach to presenting the data is as a “heatmap” where values are presented as a matrix in which each cell of the matrix is color-coded according to the concentration of the vapor measured. We can apply this method globally to all of the data on the same color scale, or use the color scale on subsets of data so that we can more clearly see relative changes within a selected sequence of data. For the current analysis I have applied the color coding uniformly **to each probe set below each tank** which yields the heat map in Figure 6. As a result, the color assigned to the maximum value below Tank 5 corresponds to 450,000 ppb whereas the same color is assigned the maximum value detected below Tank 2 of ~3800 ppb. This allows us to more easily see when the more extreme vapor concentrations occur below each tank and what their durations are and to clearly see how, and when, probes below proximal and distal tanks respond.

The values for the entire monitoring period are presented in Figure 6 with the data for each tank’s probes outlined with a black border; this figure also segregates the early vapor data, spanning March, 2008, through April, 2013, (Figure 7) from the more recent data set beginning in May, 2013, through October, 2020 (Figure 8). (Note that the cells without color are for dates when probes were not sampled due to malfunction of the probe or due to sampling of only a subset of probes on a particular date or where data are considered suspect.) A separate high resolution pdf is provided with the full data set to which the reader can refer for details of date and concentration values.

Data Analysis: For purposes of the present discussion, we will accept (nearly) all vapor values as accurate representations of the vapor phase concentration of hydrocarbons in the vadose zone below the tanks. The earlier discussion commenting on (what I understand to be) the methodology of sampling and analysis, as well as other factors that could potentially affect the vapor concentrations reported, indicates that this is not, in fact the case and, hence, conclusions drawn need to be considered in light of those cumulative uncertainties.

As noted previously, during the early years of monitoring, high vapor concentrations were found in samples recovered below the higher-numbered tanks; these show up quite clearly in the Figure 6 heatmap and are assumed to be associated with releases of varying volumes of fuel from one or more of the tanks in the upper part of the facility. The duration of the high vapor values sometimes lasted for several sampling intervals although there were also shorter episodes of high vapor values that occurred during a single month that had abated by the next sampling interval. By early 2013, the vapor values at the majority of the tanks were comparatively low.

Tank 5: Focusing initially on the probes below Tank 5, the values from May through November of 2013 were quite low, in the range of several tens to a few hundred ppb; the average for those months at the shallow, middle and deep probes were, respectively, 134 ppb, 163 ppb, and 189 ppb. In December, the values rose to 622 ppb and 794 ppb for the middle and deep probes reflecting a roughly 400% increase above the prior average and, very likely, were

induced by fuel released during the refilling of Tank 5 that began on December 9, 2013. The shallow probe remained at low levels for this sample date and suggests that the discharge from the tank's concrete encasement was likely on the opposite side, away from the tunnel, and distant from the shallowest probe inlet. During the January 15th sampling episode the middle and deep probes for Tank 5 increased to ~300 times the prior averages whereas the shallow probe showed only a doubling in value. During subsequent sampling of Tank 5, probes showed a modest decrease from the initial peak vapor concentrations through mid-March (2014), but began increasing to a second peak in mid-April of nearly twice the initial peak seen immediately after the release. Hydrocarbon vapor concentrations remained at high levels into 2015 when the deeper values started to decline and the shallow values increased to levels ten times higher than those found in contemporaneous samples from the middle and deep probes in 2016. Values have progressively declined since then, but have not yet reached levels as low as those present before the 2013 release.

The dual peaks in vapor concentrations may be associated with multiple pathways taken by the fuel after leaving the steel envelope as it migrated through the concrete encasement; we know that there were multiple leaks through the steel and there may have been multiple pathways through the concrete encasement of varying hydraulic conductivity and length. However, it should also be noted that Honolulu experienced varying rates of rainfall during the initial period following the release: some months experienced significant rainfall accumulations and other months having lower rainfall rates (monthly rainfall accumulations, in mm, are presented on the extreme right and left of the vapor data columns). A plausible mechanism for dispersal of the LNAPL within the vadose zone is a recharge event that flushes pooled LNAPL out of topographic depressions (present in the LNAPL descent trajectory) and spreads it more broadly further downslope; a much higher distribution and surface area of the LNAPL would lead to at least a temporary increase in the rate of volatilization.

Another rainfall-related alternative that should be considered is the observation, noted in the Gammon report, that groundwater is able to infiltrate into the gap space between the steel and concrete encasement – and was discharged through the “tell-tale” lines that were installed to intercept leaking fuel (these lines were subsequently removed during tank maintenance work). Groundwater, after an intense rainfall event, could infiltrate into the gap space and flush out residual fuel that had escaped the steel tank, but had not yet been able to escape the concrete encasement, and drive that fuel into the underlying formations.

Outlying Tanks: The vapor concentrations from probes for the tanks adjacent to Tank 5 also show substantial responses to the 2013/2014 release:

Probes located below Tank 3, the closest to Tank 5, show an almost immediate increase in vapor concentrations, but that increase occurs only in the deepest probe, whereas the shallower probes show a more muted and delayed response. The increase in values beneath Tank 3 are much higher in the deepest probe (which were about ten times higher than any seen at probes below Tank 4, and nearly that multiple of values seen below the tanks up-slope of Tank 5). I interpret this pattern to suggest that the high vapor values in the deep probe are the

result of LNAPL migrating downward - and down slope - below the Tank 3 deep probe and suggests that the LNAPL may have reached the water table.

Tank 4, located next-closest to Tank 5, showed more modest increases at its probes than those at Tank 3 in the January 30 sampling exercise but did show sharp increases in the March 21, 2014 sampling that were contemporaneous with the highest value in the deep Tank 3 probe. The 3/21/2014 values were ~100 times higher than prior averages, but never approached the magnitude of the highest Tank 3 deep probe values. Also notable in the Tank 4 (3/21/2014) values is that we don't see as great a divergence between the deep and shallow probe values; this suggests that the LNAPL source for the vapors is likely located at a greater distance from these probes. There are also sharply elevated values below Tank 4 in the January and May (2015) sampling exercises that may be related to the 2013/2014 release; these will be discussed below.

Tank 2 probes, located farthest downslope of Tank 5, maintained low values through March, 2014, but showed values well above prior averages by May, 2014, and remained higher than previous averages through 2019 (with some occasional spikes to much higher values in 2015 that will be discussed below).

Probes for Tanks 6, 7, 8, and 9, located up-slope of Tank 5, also showed significant increases above their prior averages. These increases occurred nearly simultaneously with the initial extreme values at Tank 5 in mid-January, 2014. Initial values below Tank 6 were about 30 times lower (3%) than those at Tank 5 probes, but the values at the closer tanks gradually rose to ~10% of the Tank 5 levels over the next several weeks. The more distant tanks showed progressively lower concentrations, with increasing distance, relative to Tank 5 vapor levels, but vapor values at probes beneath Tanks 10 through 12 also appear to have been impacted by the release at Tank 5 with more modest increases in concentrations. The values beneath the upper tanks, with exceptions that will be discussed below, gradually decline toward their prior values and begin to reach levels similar to their averages prior to the 2013/2014 release by 2018.

Probes below Tanks 13 through 16 during this period also show significant vapor concentration increases as well. However, Tank 17 showed significant hydrocarbon vapor concentrations as early as 5/13/13 (prior to the Tank 5 release) and makes any attempt to interpret possible impacts of the Tank 5 release on vapor concentrations in this area of the tank farm problematic and will not be attempted.

Interpretation of Vapor Concentration Variations Subsequent to 2013/2014 Release

Although the observed behavior of the vapor concentrations is, at best, difficult to uniquely attribute to a specific set of circumstances within the vadose zone, there are plausible interpretations of the responses observed. The data from the probes below Tank 5 suggest the following:

1. Vapor values below Tank 5 began within days of the start of filling operations at Tank 5. Although the increased vapor concentrations were not extraordinary (within the context of

variations seen within the entire data set), they were substantially higher than prior averages and occurred during a critical operation that was underway at Tank 5.

2. The increase in vapor concentrations was not monotonic: vapor values increased to an initial peak, then fell significantly before rising to their highest levels about five months after the tank filling operations began (and more than three months after the tank had been drained). This suggests that there were multiple release pathways (or mechanisms). One plausible explanation for the observed pattern is that residual fuel had accumulated between the inner steel envelop and the concrete encasement. Some of that fuel was released immediately, but the residual escaped after the bulk of the fuel had been drained from inside the steel tank. The distribution of the vapor concentrations is consistent with this: the initial high vapor value was observed in the deep/outer probe; the second peak in vapor concentrations showed about equal concentrations at the central/mid-depth and the deep/outer probe whereas the shallow/inner probe reaches concentrations no higher than half those of the other two. As noted above, the role of rainfall/groundwater in transporting and dispersing the released fuel is uncertain, but cannot be dismissed. The release occurred during a period of moderately high rainfall accumulations and, as noted previously, the Gammon report details observations of groundwater infiltrating the space between the steel tank walls and the concrete encasement. Further discussion of rainfall and its effects on vapor concentrations will be presented below.

The vapor values observed in the tanks located lower than (southwest of) Tank 5 in Redhill Ridge are interpreted as follows:

3) Increased vapor concentrations were observed at the deep probe below Tank 3 very soon after high values were observed at Tank 5 (it is unfortunate that Tank 3 probes were not sampled simultaneously with those at Tank 5 on January 15, 2014; they might have further confirmed that a release was underway). Clearly there was gas phase transport of LNAPL volatiles from Tank 5 to the Tank 3 probes almost immediately after discharge into the vadose zone.

4) The Tank 3 deep probe continued to increase during the following two months and reached a value substantially higher than any concentration observed below other outlying tanks around Tank 5 and, in fact, exceeded the highest measured value below Tank 5 during that sampling round by more than 50%. These high values, as well as the strong gradient from the deep/outer probes to the shallow/inner probes, is interpreted to indicate that LNAPL flowed down the strike and dip of the lava flows within the ridge and passed in close proximity to, and below, the deeper probe. The apparently (here again, a more aggressive sampling program would have provided more definitive data) rapid fall-off in concentrations from that peak suggests that the LNAPL continued to migrate downward and out of range of the deeper Tank 3 probe.

5) As discussed below, a second factor in the rapid decline of vapor values below Tank 3 and its companions is attributed to active, thermally driven, gas phase transport through the ridge along the strike and dip of the lava beds. Thermally driven advective transport would be

expected to draw less-volatile-rich air from downslope (the southwest end of the ridge) and carry it towards the northeast, up slope, toward the higher-numbered tanks.

6) Vapor values below Tanks 2 and 4 showed more modest, and more evenly distributed, vapor concentrations that I attribute to gas phase transport and dispersion. Increases in concentration occur at Tank 4 relatively soon after elevated values appear below Tank 3 whereas Tank 2 shows a significant increase above prior values about three months after the release began. Here, again, there was not consistent sampling throughout the area and, hence, values may have been increasing below Tank 2 nearly a month earlier.

The vapor values observed in the tanks located higher than (east and northeast of) Tank 5 in Redhill Ridge are interpreted as follows:

7) The very rapid rise in vapor values below Tanks 6 through 10 (January 15 and 30, 2014) is strong evidence for vapor phase transport from the point of discharge into the vadose zone toward the NE. Although the initial rise in vapor concentrations below these tanks is rapid, the magnitude of the early values is modest (<7000 ppb at the highest). The second peak in concentrations at Tank 5, in March, 2014, is accompanied by vapor concentrations that were as much as six times higher than those seen previously at both the odd-numbered (directly up-ridge) and the even-numbered (across-ridge) tanks and suggest a much larger source of hydrocarbon volatiles. The distribution of concentrations also appears to be quite uniform, not showing a strong gradient from shallow (near tunnel) to deep (outside edge of the tanks); there is, however, a fairly strong gradient between the odd- and even-numbered tanks with the latter showing values that are half or less than the values of their odd-numbered “companion” tank. The much higher values imply a larger source and may reflect LNAPL from the release that reached the water table and spread over a much larger surface area for the fuel to be volatilized from. Although this hypothesis is by no means a unique explanation for the recorded values, it is consistent with them.

8) The great disparity in the vapor concentrations found below the tanks southwest of Tank 5 and those east and northeast (as much as fifty times higher in the northeast), is consistent with a strong advective flow of subsurface vapor toward the northeast along the strike and dip of the lavas within the ridge. The temperature measurements made in the monitoring wells, as well as the orientation of higher and lower concentrations, suggest that this is thermally driven advective transport. (In the absence of a heat source, the addition of (most) hydrocarbon vapors will increase the density of an air mass resulting in downward flow and, hence is inconsistent with the observed data).

Short-term/episodic Vapor Concentration Variations

Within the entire data set there are a number of shorter term variations in vapor concentrations that are not associated with the Tank 5 release. I will not attempt to evaluate the majority of them: some, where high values persist beneath a given tank for an extended period of time, can reasonably be inferred to be associated with a fuel release of some magnitude. Other, one-time, high value vapor readings, are more likely due to equipment malfunction (whether of the probes or the PID).

There are other sets of readings that are more problematic. We see an unusual pattern in the measurements made on 10/27/14, 1/28/15, and 5/28/15: all are associated with anomalously low values for most of the probes below tanks up-ridge from Tank 5. The 10/27/14 values in the tanks below Tank 5 are somewhat depressed compared to those before and after that date, but the values observed for the probes below Tanks 2 and 4 are substantially elevated (by factors of as much as 10 or more) above the prior or following values for each probe. Whether these deviations are associated with instrument malfunction or with an environmental change (e.g. rainfall) is not at all clear. Rainfall accumulations during the months of the first two sets of anomalous values were quite high, and above average, respectively; the rainfall for the third set of data was normal to low.

Another set of data that stands out is the sampling round of 9/30/15: it too shows a one-time significant decrease in vapor concentrations relative to prior and following values, for the majority of the probes sampled. This suite of values is also associated with unusually high rainfall accumulations, but also correlates with a change in contractor from ESI to Element Environmental. During prior change-overs from one contractor to another, we see a similar (although not identical) pattern in decreasing values for the first one or two sampling rounds.

We can also see a sudden, continuing change in the values for Tank 18 beginning in June, 2019, when values decreased at the two functional probes, shallow and deep, from an average of ~5000 ppb to an average of ~500 to 800. This change, discussed in the review of the sampling protocols, occurred when, according to the contractor, the tubing used in the sampling process was changed.

Analysis

The above observations are significant, and worthy of examination, because the 2013/2014 release produced a small but significant (~4X) increase in vapor concentrations below Tank 5 within days of the time filling operations began; had the Navy been able to respond appropriately to those increases, the volume of fuel released, and potential for impacts to drinking water supplies, could have been reduced by an order of magnitude. However, the scale of variations that typically occur in the vapor data – that are not (likely) associated with a fuel release event – have much larger magnitudes than the changes that occurred during the early stages of the 2013/2014 release. If we can better understand the source of these variations, and, where possible, reduce or eliminate those associated with incorrect or imprecise field protocols, then this expensive and time consuming effort can better meet the objective of reducing fuel losses and reducing the impacts of those losses on the underlying groundwater.

A definitive analysis of the vapor variations associated with rainfall rates is challenging. As noted, there are a number of significant – if contradictory – variations associated with large monthly rainfall accumulations. That association is somewhat indirect: the changes in vapor concentrations don't usually occur during the month of high rainfall, but more typically a month or more after the peak rainfall accumulation. There are also episodes of large accumulations of rainfall that show only modest, or isolated, variations.

There are several plausible, if not unique, explanations for the observed vapor concentration responses to rainfall events. A significant rainfall event will result in sub-horizontal water flow along the strike and dip of the stratigraphy within Redhill Ridge; this behavior has been observed nearby in the open face of the Halawa Quarry where water will flow out of the clinker layers between the massive a'a interior units. As noted above, gas phase transport allows rapid movement of hydrocarbon vapors across substantial distances within the ridge. Introduction of large quantities of recharge water has the potential to saturate formations that were previously more open to vapor transport and effectively, and temporarily, "turn off" that long range transport of LNAPL volatiles. Alternatively, the driving force for that advective transport can plausibly be assigned to the thermal effects arising from biodegradation of residual LNAPL in the vadose zone: a significant rainfall recharge event could effectively cool the formation and, again, temporarily "turn off" the energy source for long distance transport of the volatiles.

The "contradictory" response, the significant increases in volatile vapor concentrations after large rainfall accumulations are, as discussed above, plausibly assigned to mobilization of residual or pooled LNAPL, either in the formation or within the tanks' encasements, out into the vadose zone where volatilization of the LNAPL will be detected by the vapor probes. This hypothesis is, to a degree, supported by the fact that an apparent association between rainfall and elevated values only occurs when there is other evidence for a prior release and only in proximity to that assumed release (e.g. in addition to the observations around Tank 5, Tank 18 shows elevated values from April 2014 through February 2015; higher than normal values are recorded below Tanks 14 through 16 in late May, 2016, a month that also experienced higher than normal rainfall). We note too, that since February, 2017, there hasn't been a month with a particularly large accumulation of rainfall and there has, likewise, been no clear evidence of significant reductions/increases having this pattern (with the possible exception of the most recent data when new sampling protocols were implemented).

Summary

The important findings of the present analysis are as follows:

- 1) Subsurface vapor concentrations respond very quickly to introduction of LNAPL into the vadose zone around the Red Hill tanks;
- 2) There is gas phase transport of LNAPL volatiles over significant distances within Red Hill Ridge. The most likely driving force for gas phase transport within the ridge is thermal advection driven by heat produced by biodegradation of residual LNAPL within the vadose zone or in the underlying groundwater (or both).;
- 3) In addition to the changes in vapor concentrations associated with fresh releases, there is significant variability in concentration values that is likely induced by a combination of environmental variables (rainfall, possibly wind driven pressure gradients, etc.), possible anthropogenic variables (pressure variations within the tunnels), and the interaction of these variables with long range advective transport.

- 4) In addition to the above interaction, there may also be interactions between rainfall recharge and pooling of LNAPL within the concrete encasement or in the basalt after the LNAPL is discharged from the steel tanks;
- 5) There is clear evidence of variability in the reported vapor concentrations related to the field procedures applied during the sampling and analysis campaigns.

Recommendations

- 1) The highest priority task is to conduct an audit of the field procedures to determine whether current sampling procedures are providing accurate, reliable, and reproducible analytical results representative of hydrocarbon vapor concentrations from the individual probes.
- 2) Where probe lines are malfunctioning or plugged, those probe lines, or probe sets, should be removed and replaced with functional probes.
- 3) An analysis, validation, and response procedure should be established that:
 - a. establishes a reasonable set of dynamic concentration thresholds for each probe (e.g. 500% increase above prior four-month average);
 - b. recognizes that long-range transport of hydrocarbon vapors is occurring and that rainfall and other natural and anthropogenic events may be impacting the subsurface vapor concentrations measured;
 - b. implements a process for resampling and re-analysis of vapor from probes that exceed those thresholds to confirm the relative exceedance (e.g. resampling 24/48/72 hours later);
 - c. an appropriate SOP if the elevated values are confirmed (e.g. continued close monitoring, tank tightness, or increased fuel level monitoring) or show a continuing/accelerating increase (e.g. begin preparations required for draining tank) in the absence of other factors that are known to yield anomalously high values.
- 4) Modify reporting procedures so that, in particular, anomalous vapor levels can be evaluated by trained, responsible individuals who are authorized to initiate appropriate actions when presented with evidence that a significant release may be underway.
- 5) If/when a continuous monitoring program is implemented, an integrated data set (probe location, apparent permeability around each probe, etc.) will need to be evaluated for environmental and anthropogenic impacts on vapor values as well as the varying characteristics of the stratigraphy within which the probes are mounted. The more frequent/continuous monitoring results will enable a much refined analysis to be conducted of the relationship among vapor concentrations and environmental (e.g. rainfall, barometric pressure, etc.) and anthropogenic variables (e.g. tank operations, adit pressures, etc.) to allow more certain identification of release events.

6) Although the interpretation of the data that suggests the possibility that rainfall events allow infiltration of groundwater into the space between the steel envelop and concrete encasement is by no means certain, it does suggest that monitoring of that space could also provide extremely valuable information. There has been discussion of removal of smaller nozzle connections from beneath the tanks; if the existing pipelines connected to those nozzles could be repurposed for use as monitoring ports (and drains) for the space behind the steel envelope, they may be able to provide earlier indications of small and/or increasing leakage from the tanks that could be identified and remediated before the release rate reached the outside environment (and reduce the volume escaping from the concrete encasement).

Acknowledgements

Field observations critical to the analysis and interpretation of the field procedures and the data were provided by Hugh Meyers; Gary Becket provided valuable recommendations on testing of the vapor probes; and Fenix Grange provided reviews of the document drafts and suggested improvements to the overall text.

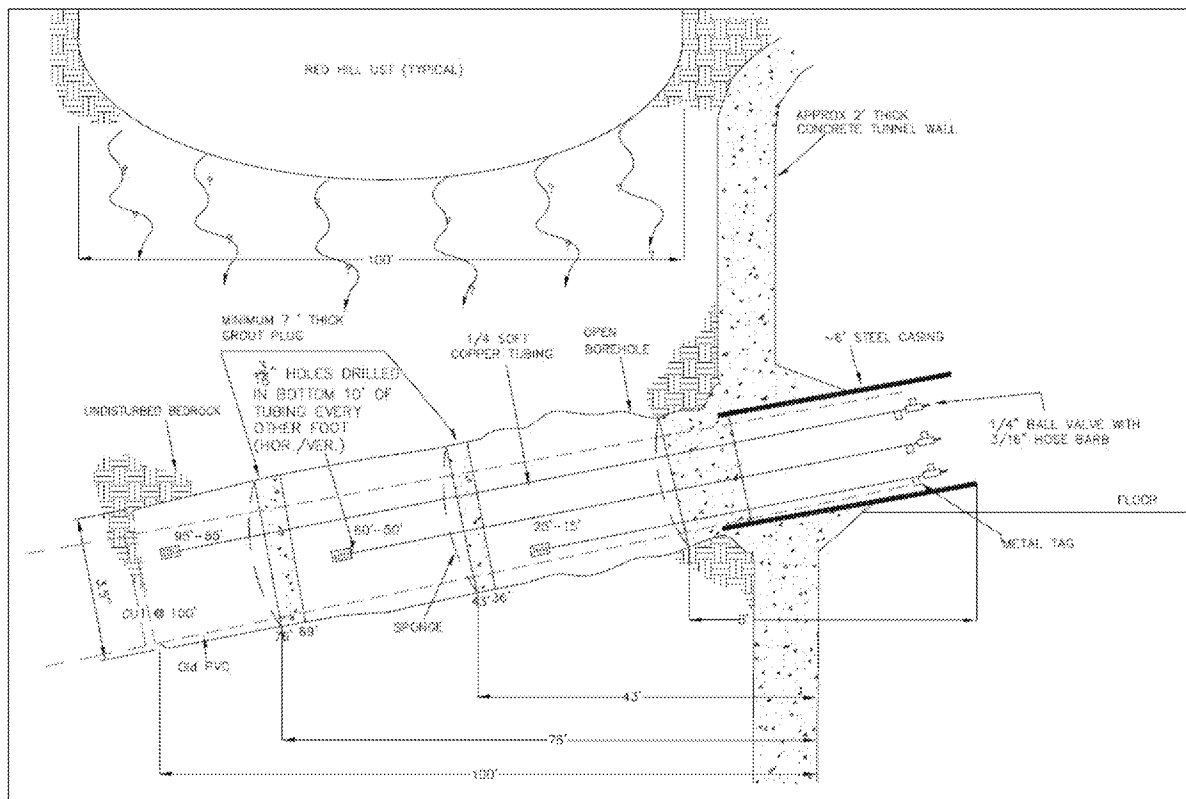


Figure 1. Schematic diagram of installation of soil vapor probes.

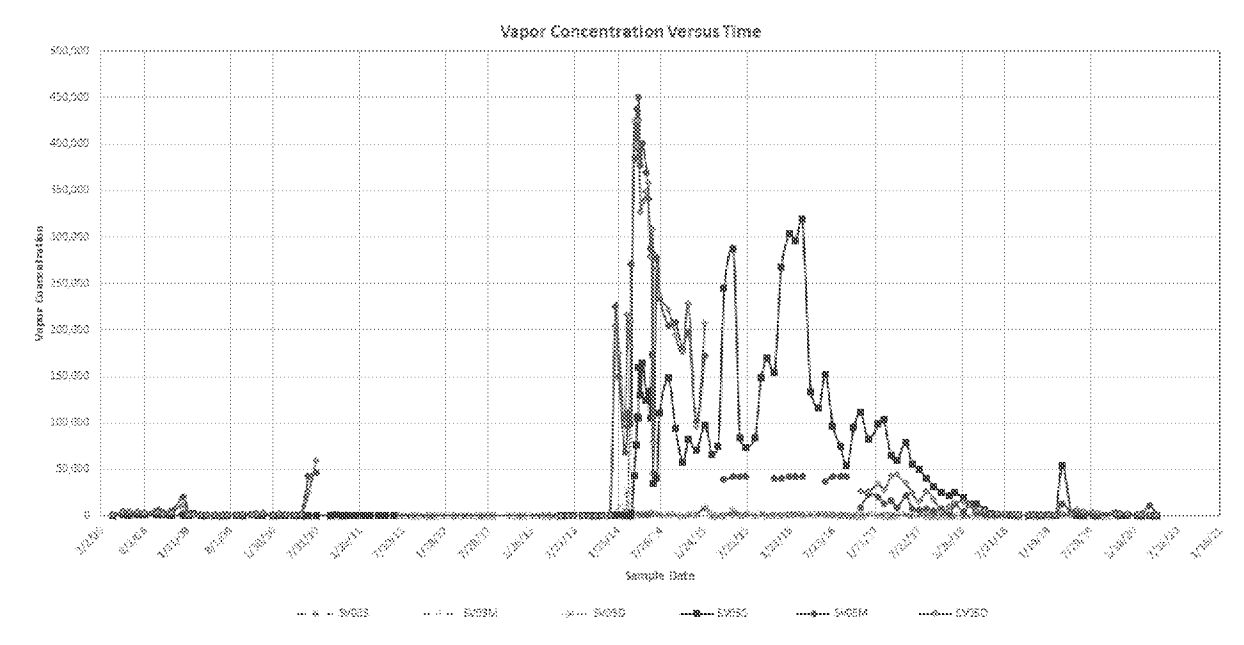


Figure 2. Concentration versus time on linear concentration axis

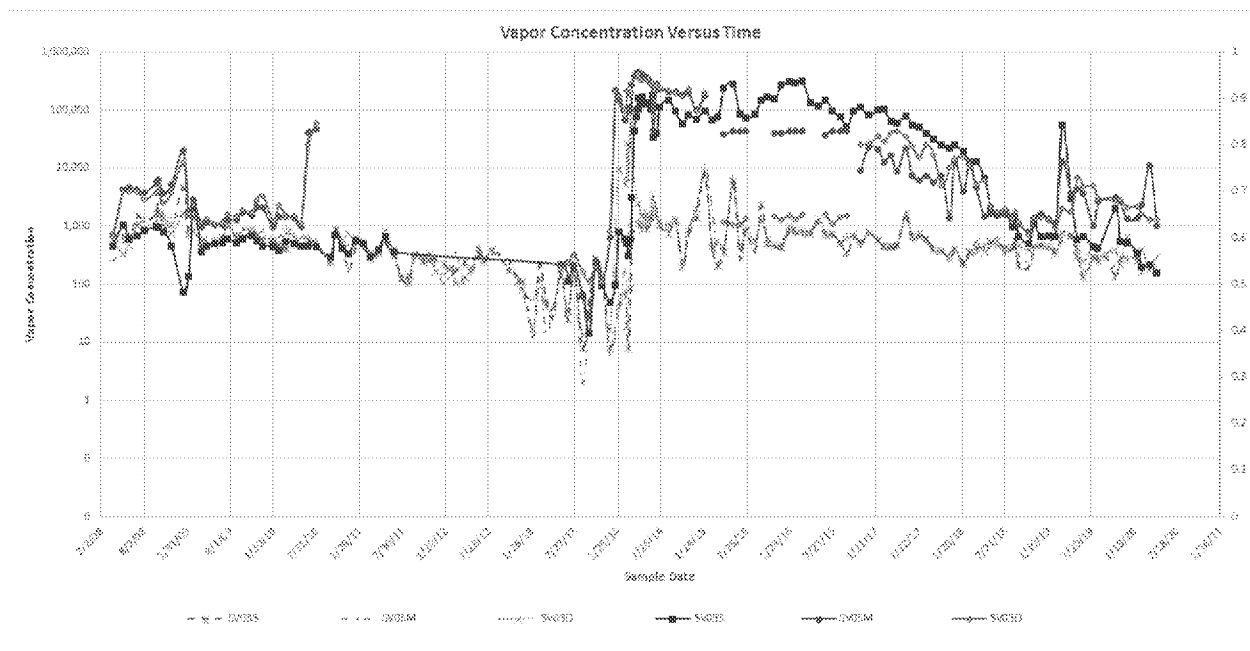


Figure 3. Concentration versus time on a logarithmic concentration axis

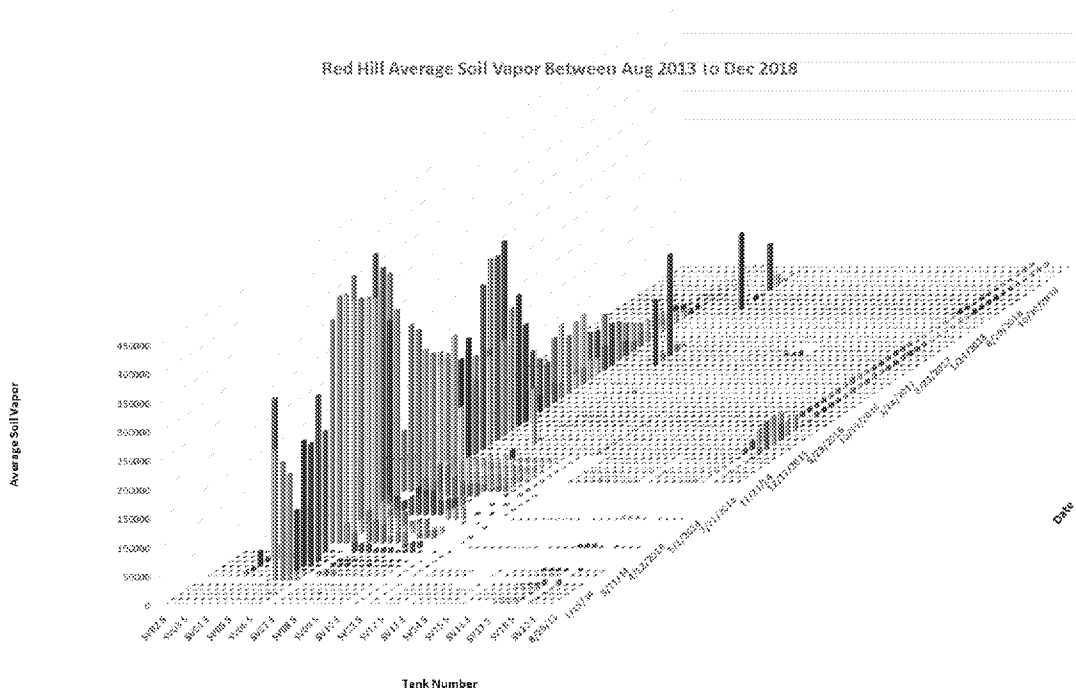


Figure 4. Waterfall plot of Red Hill vapor data from August, 2013, to December, 2018 with vertical axis as a linear scale.

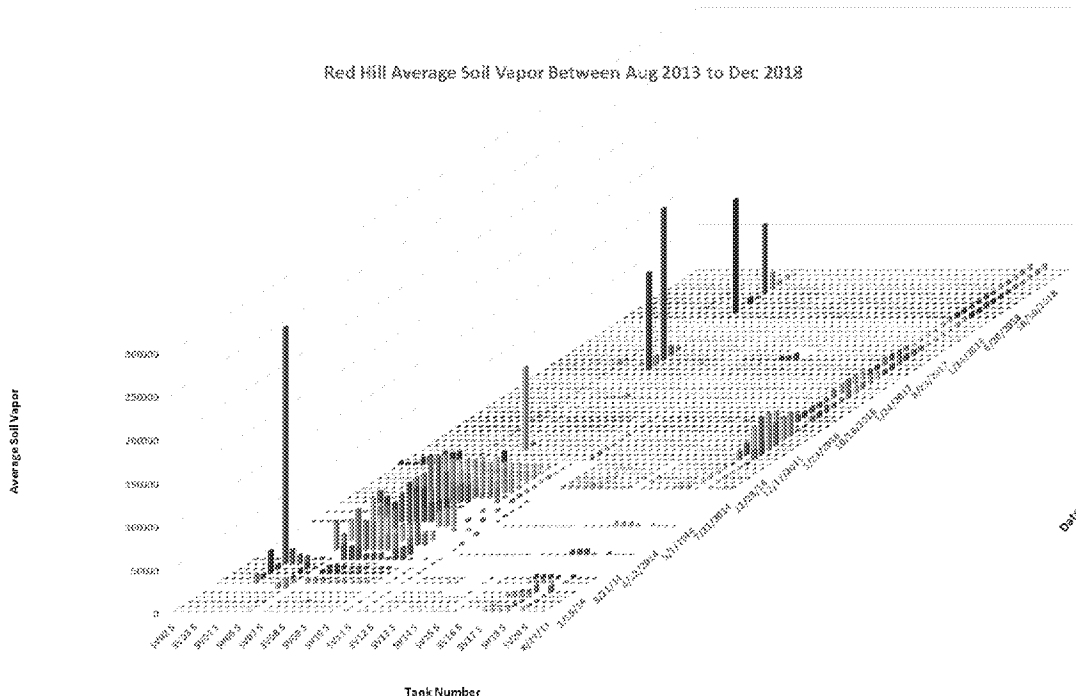


Figure 5. Waterfall plot of Red Hill vapor data without Tank 5 probes. The impact of the release at Tank 5 on vapor values at the probes for the surrounding tanks is evident.

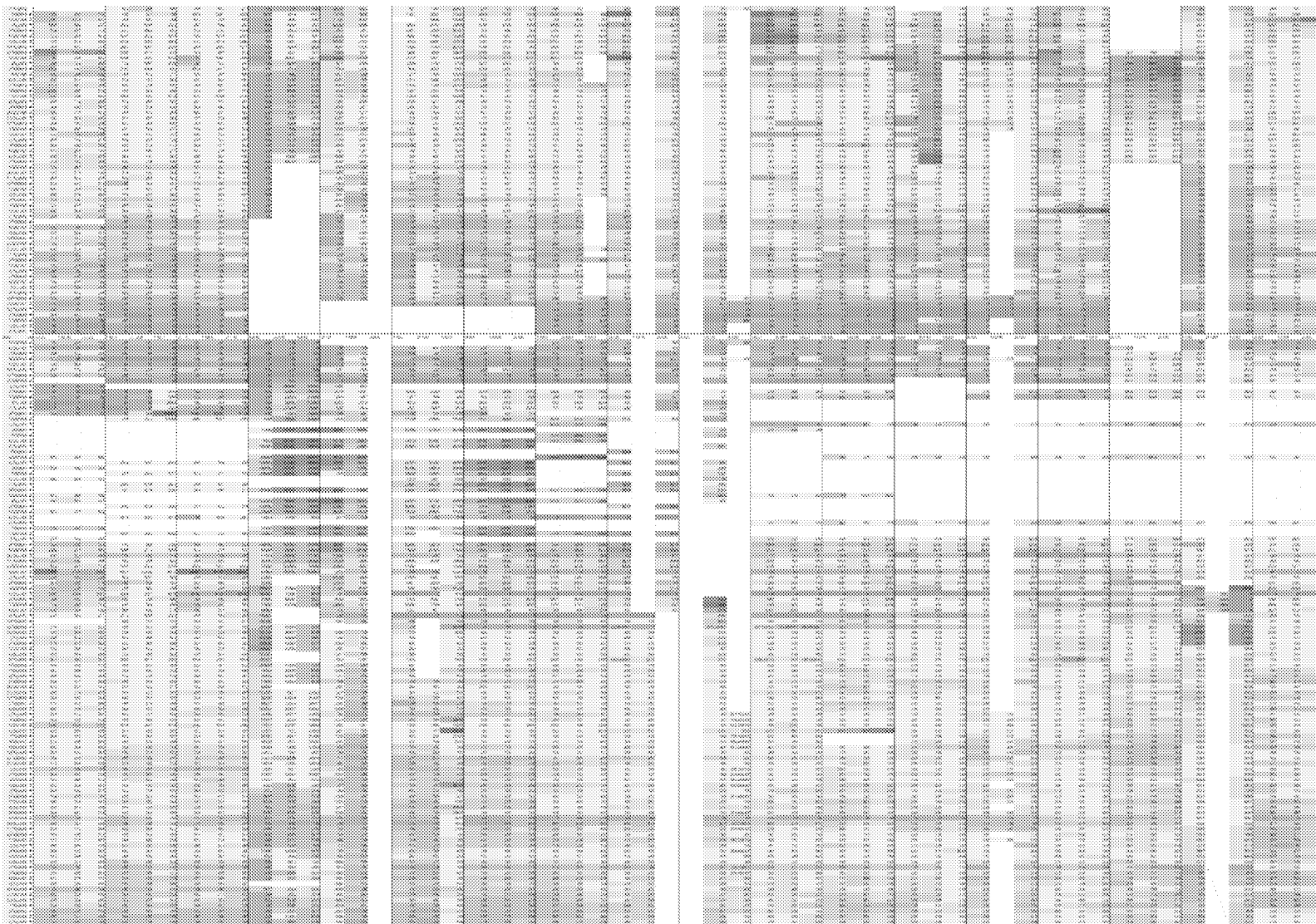


Figure 6. A heatmap of the entire set of Red Hill soil vapor data from March, 2008, through April, 2020. Although not readable at this scale, each colored cell contains a vapor concentration value; the color scheme has red associated with the highest concentrations of organic vapor; yellow is intermediate, and green is lower vapor concentrations. The dark vertical lines separate the set of three probes for each of the tanks; the color coding is for the values within each set of three probes. The earlier data is at the top and become more recent downward; the lower numbered tanks are on the left and progress to higher tank numbers on the right. Cells without color are dates or probes for which data was not collected on the date plotted.



Figure 7. Heatmap for vapor concentration data recovered beginning in May, 2013 through April of 2020.



Rainfall Acc.		SV01		SV02		SV03		SV04		SV05		SV06		SV07		SV08		SV09		SV10		SV11		SV12		SV13		SV14		SV15		SV16		SV17		SV18		SV19		SV20		SV21		SV22		SV23		SV24		SV25		SV26		SV27		SV28		SV29		SV30		SV31		SV32		SV33		SV34		SV35		SV36		SV37		SV38		SV39		SV40		SV41		SV42		SV43		SV44		SV45		SV46		SV47		SV48		SV49		SV50		SV51		SV52		SV53		SV54		SV55		SV56		SV57		SV58		SV59		SV60		SV61		SV62		SV63		SV64		SV65		SV66		SV67		SV68		SV69		SV70		SV71		SV72		SV73		SV74		SV75		SV76		SV77		SV78		SV79		SV80		SV81		SV82		SV83		SV84		SV85		SV86		SV87		SV88		SV89		SV90		SV91		SV92		SV93		SV94		SV95		SV96		SV97		SV98		SV99		SV100		SV101		SV102		SV103		SV104		SV105		SV106		SV107		SV108		SV109		SV110		SV111		SV112		SV113		SV114		SV115		SV116		SV117		SV118		SV119		SV120		SV121		SV122		SV123		SV124		SV125		SV126		SV127		SV128		SV129		SV130		SV131		SV132		SV133		SV134		SV135		SV136		SV137		SV138		SV139		SV140		SV141		SV142		SV143		SV144		SV145		SV146		SV147		SV148		SV149		SV150		SV151		SV152		SV153		SV154		SV155		SV156		SV157		SV158		SV159		SV160		SV161		SV162		SV163		SV164		SV165		SV166		SV167		SV168		SV169		SV170		SV171		SV172		SV173		SV174		SV175		SV176		SV177		SV178		SV179		SV180		SV181		SV182		SV183		SV184		SV185		SV186		SV187		SV188		SV189		SV190		SV191		SV192		SV193		SV194		SV195		SV196		SV197		SV198		SV199		SV200		SV201		SV202		SV203		SV204		SV205		SV206		SV207		SV208		SV209		SV210		SV211		SV212		SV213		SV214		SV215		SV216		SV217		SV218		SV219		SV220		SV221		SV222		SV223		SV224		SV225		SV226		SV227		SV228		SV229		SV230		SV231		SV232		SV233		SV234		SV235		SV236		SV237		SV238		SV239		SV240		SV241		SV242		SV243		SV244		SV245		SV246		SV247		SV248		SV249		SV250		SV251		SV252		SV253		SV254		SV255		SV256		SV257		SV258		SV259		SV260		SV261		SV262		SV263		SV264		SV265		SV266		SV267		SV268		SV269		SV270		SV271		SV272		SV273		SV274		SV275		SV276		SV277		SV278		SV279		SV280		SV281		SV282		SV283		SV284		SV285		SV286		SV287		SV288		SV289		SV290		SV291		SV292		SV293		SV294		SV295		SV296		SV297		SV298		SV299		SV300		SV301		SV302		SV303		SV304		SV305		SV306		SV307		SV308		SV309		SV310		SV311		SV312		SV313		SV314		SV315		SV316		SV317		SV318		SV319		SV320		SV321		SV322		SV323		SV324		SV325		SV326		SV327		SV328		SV329		SV330		SV331		SV332		SV333		SV334		SV335		SV336		SV337		SV338		SV339		SV340		SV341		SV342		SV343		SV344		SV345		SV346		SV347		SV348		SV349		SV350		SV351		SV352		SV353		SV354		SV355		SV356		SV357		SV358		SV359		SV360		SV361		SV362		SV363		SV364		SV365		SV366		SV367		SV368		SV369		SV370		SV371		SV372		SV373		SV374		SV375		SV376		SV377		SV378		SV379		SV380		SV381		SV382		SV383		SV384		SV385		SV386		SV387		SV388		SV389		SV390		SV391		SV392		SV393		SV394		SV395		SV396		SV397		SV398		SV399		SV400		SV401		SV402		SV403		SV404		SV405		SV406		SV407		SV408		SV409		SV410		SV411		SV412		SV413		SV414		SV415		SV416		SV417		SV418		SV419		SV420		SV421		SV422		SV423		SV424		SV425		SV426		SV427		SV428		SV429		SV430		SV431		SV432		SV433		SV434		SV435		SV436		SV437		SV438		SV439		SV440		SV441		SV442		SV443		SV444		SV445		SV446		SV447		SV448		SV449		SV450		SV451		SV452		SV453		SV454		SV455		SV456		SV457		SV458		SV459		SV460		SV461		SV462		SV463		SV464		SV465		SV466		SV467		SV468		SV469		SV470		SV471		SV472		SV473		SV474		SV475		SV476		SV477		SV478		SV479		SV480		SV481		SV482		SV483		SV484		SV485		SV486		SV487		SV488		SV489		SV490		SV491		SV492		SV493		SV494		SV495		SV496		SV497		SV498		SV499		SV500		SV501		SV502		SV503		SV504		SV505		SV506		SV507		SV508		SV509		SV510		SV511		SV512		SV513		SV514		SV515		SV516		SV517		SV518		SV519		SV520		SV521		SV522		SV523		SV524		SV525		SV526		SV527		SV528		SV529		SV530		SV531		SV532		SV533		SV534		SV535		SV536		SV537		SV538		SV539		SV540		SV541		SV542		SV543		SV544		SV545		SV546		SV547		SV548		SV549		SV550		SV551		SV552		SV553		SV554		SV555		SV556		SV557		SV558		SV559		SV560		SV561		SV562		SV563		SV564		SV565		SV566		SV567		SV568		SV569		SV570		SV571		SV572		SV573		SV574		SV575		SV576		SV577		SV578		SV579		SV580		SV581		SV582		SV583		SV584		SV585		SV586		SV587		SV588		SV589		SV590		SV591		SV592		SV593		SV594		SV595		SV596		SV597		SV598		SV599		SV600		SV601		SV602		SV603		SV604		SV605		SV606		SV607		SV608		SV609		SV610		SV611		SV612		SV613		SV614		SV615		SV616		SV617		SV618		SV619		SV620		SV621		SV622		SV623		SV624		SV625		SV626		SV627		SV628		SV629		SV630		SV631		SV632		SV633		SV634		SV635		SV636		SV637		SV638		SV639		SV640		SV641		SV642		SV643		SV644		SV645		SV646		SV647		SV648		SV649		SV650		SV651		SV652		SV653		SV654		SV655		SV656		SV657		SV658		SV659		SV660		SV661		SV662		SV663		SV664		SV665		SV666		SV667		SV668		SV669		SV670		SV671		SV672		SV673		SV674		SV675		SV676		SV677		SV678		SV679		SV680		SV681		SV682		SV683		SV684		SV685		SV686		SV687		SV688		SV689		SV690		SV691		SV692		SV693		SV694		SV695		SV696		SV697		SV698		SV699		SV700		SV701		SV702		SV703		SV704		SV705		SV706		SV707		SV708		SV709		SV710		SV711		SV712		SV713		SV714		SV715		SV716		SV717		SV718		SV719		SV720		SV721		SV722		SV723		SV724		SV725		SV726		SV727		SV728		SV7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